

# On some properties of Deuteron and Antideuteron production in high energy lead-lead collisions at 158A GeV

Goutam Sau<sup>1\*</sup> & S. Bhattacharyya<sup>2†</sup>

<sup>1</sup> Beramara RamChandrapur High School,  
South 24-Pgs, 743609(WB), India.

<sup>2</sup> Physics and Applied Mathematics Unit(PAMU),  
Indian Statistical Institute, Kolkata - 700108, India.

## Abstract

We would attempt here to understand some properties of the transverse momentum ( $p_T$ ) and rapidity ( $y$ ) spectra on production of deuteron ( $d$ ) and antideuteron ( $\bar{d}$ ) in lead-lead ( $Pb + Pb$ ) collisions at 158A GeV recently reported by NA49 collaboration. Starting from some basic properties of  $p + p$  reactions for production of secondary proton-antiprotons the cases of production of the composite set of particles, like  $d$  and  $\bar{d}$ , would be analysed. Some ratio-behaviours would also be dealt with in the light of the same approaches. It is found that the combination of the models put into use here capture modestly well the trends of the data on some important observables. Some limitations of the approach would also be pointed out in the end.

Keywords: Inclusive cross-section; relativistic heavy ion collision; cluster formation.

PACS nos.: 13.60.Hb; 25.75.-q; 82.33.Fg.

---

\*e-mail: sau-goutam@yahoo.com

†e-mail: bsubrata@www.isical.ac.in (Communicating Author)

# 1 Introduction

Studies on baryon-antibaryons and light composite cluster formation[1]-[4] constitute now a very important corner from both theoretical and experimental viewpoints comprising particle physics and astroparticle physics aspects. The observations and measurements on deuteron and antideuteron production in relativistic heavy-ion collisions, it is believed, could probe the later stages of the evolution of hypothesized new state of strongly interacting matter, called Quark-Gluon Plasma (sQGP)[5]-[9]. It is also taken for granted that after the initial expansion of QGP matter and subsequent cooling, nucleons (antinucleons) in spatial proximity and with neighbouring momenta might coalesce to form light nucleus (antinucleus) clusters. The sensitivity of light-nucleus production to the space-time evolution of the interaction region and collision dynamics imparts such studies on them a special degree of importance, and render them quite relevant.

The interests in such studies on light cluster formation particle like deuteron-antideuteron, triton-antitriton, helium-antihelium etc spring, in the main, from (i) the prediction of excess antibaryon[10, 11] (antimatter) production in central nucleus-nucleus collisions relative to  $p+p$  in the QGP phase. It is claimed that if antibaryon abundances are not in equilibrium or not strongly affected by annihilation after chemical freeze-out some of the initial enhancement may survive till the final stage of the collision process at the end of which secondary particles begin to emanate; (ii) the persistent controversies around the observations of excess of matter over antimatter against the general background of matter-antimatter asymmetry[12]-[15].

In the present work we primarily concern ourselves with the understanding of some features of very recent experiments on  $d$ ,  $\bar{d}$  production at various centrality by NA49 collaboration in high energy  $Pb + Pb$ [1] collisions. This study by NA49 collaboration is the first report that came to light with measurements on  $d$  and  $\bar{d}$  at various centralities in high energy  $Pb + Pb$  collisions, for which this measurement has assumed high degree of prominence. And just because of it, we have been attracted to this fresh bid of study on  $d$  and  $\bar{d}$  production in  $Pb + Pb$  collisions at 158A GeV.

The outline of our approach is as follows. Against the general background of what is known as the coalescence picture, the explanation is attempted with the help of a new combination of models (NCM), of which the first one is for nucleon-nucleon collision and the other one is for nucleus-nucleus interactions as is detailed in the next paragraph. Besides, a new parametrization for the nature of mass number (A) dependence for nucleus-nucleus interactions is introduced. And by making use of all of them we will first try here to explain the nature of  $p_T$ -spectra on  $d$  and  $\bar{d}$  production in nucleus-nucleus collisions. Thereafter, we will attempt to interpret, in addition, characteristic properties of the newly obtained data on rapidity spectra of  $d$  and  $\bar{d}$  in the same reactions at relatively high energies.

The model for nucleon-nucleon interactions used here was formulated and forwarded long ago by Hagedorn[16] which has been extensively used by us in interpreting the various aspects[17, 18] of high energy particle and nuclear collisions. Thus, our next objective here is to check whether Hagedorn's Model (HM) can also be used for interpreting the deuteron-antideuteron production phenomena, and which would, in turn, also help us to check whether the final working formula utilized here for building up of a straight corridor between nucleon-nucleon and nucleus-nucleus collisions would be sufficiently effective or not. However, the antideuteron data are too sparse and they suffer from high degree of measuremental uncertainties with large error bars for which they hardly suffice to make the study very convincing.

Some other preemptive comments are in order here. First, in the present work, we are not going to offer any new insights into or any refinements of the used coalescence picture. Second,

experimental data points on the coalescence factor have been used here as an indirect way to assess the merit and utility of the NCM. Besides, the combination of the models that are used here also attempts to explain the features of transverse momenta spectra of antiprotons and antideuteron in nucleon-nucleon collisions at high energies, and some related features of antideuteron production as well. Third, we attempt to interpret the available limited data on rapidity-dependence properties of the same species ( $d$  &  $\bar{d}$ ) with the same combinational approach. Fourth and final, we are certainly not going to dwell upon the present issues of antideuteron production against the broad background of any general matter-antimatter controversy, because this is beyond the purview of the present study.

The plan of the paper is as follows : In Section 2 we give a brief outline of the basic Coalescence Approach (CA). Section 3 and Section 4 provides the tools, that is, the synopses of the models which are put into use here as the two principal concerns of this study. In Section 5 we summarise the calculational results based on the models of our choice. The last section is for final discussion and conclusion.

## 2 The Coalescence Model : In a Nutshell

It is well known that the studies on deuteron production are commonly grounded on the tacit acceptance of the coalescence picture. According to this view, deuteron production with a certain velocity is proportional to the number of antiprotons and neutrons that have similar velocities; and the coalescence factor is contingent upon the distribution of nucleons. This property guides us to determine the source size of the nucleon from the ratio defined, one assumes, by the form[19, 20] :

$$B_2(p) = \frac{E_d \frac{d^3 N_d}{dP^3}}{(E_p \frac{d^3 N_p}{dp^3})^2} \quad (1)$$

Wherein  $B_2(p)$  is termed the ‘coalescence parameter’ which is inversely proportional to the volume of the particle source, and wherein the yield of neutrons is supposed to be equal to that of protons. The deuteron momentum  $P$  is twice the antiproton momentum  $p$ . Measurement of neutrons is normally avoided. The factor in subscript of  $B$  represents simply the fact whether deuteron/antideuteron or any other antiparticle-particle pair is being studied.

## 3 Present Approach : A Brief Outline of the New Combinational Model (NCM)

This subsection dwells upon the adopted methodology for  $p_T$  studies of  $p(\bar{p})$  or  $d(\bar{d})$ . The generalized form of the inclusive cross-section for production of either antiproton or antideuteron is taken to be represented here by

$$E \frac{d^3 \sigma}{dp^3} |_{P+P \rightarrow Q+X} = C_1 (1 + \frac{p_T}{p_0})^{-n} \quad (2)$$

where  $Q$  stands for the secondary particle produced in any specific collisions,  $p_T$  is the transverse momentum of  $Q$ , and  $C_1$ ,  $p_0$ ,  $n$  are the constants. The above form presented by expression (2) is an obvious adaptation of HM[16] for particle production in nucleon-nucleon collisions.

But in the present study we are interested to pursue a particular aspect of the nucleus (A)-nucleus (B) collisions, for which we try to build up a bridge or linkage between nucleon-nucleon

( $p+p$ ) and nucleus-nucleus ( $A+B$ ) collisions. With a view to obtaining such a connective route, let us propose here a form as was prescribed first by Peitzmann[21] which we refer to as Peitzmann's Approach (PA) and was utilized by us in some previous work[22, 23] :

$$E \frac{d^3\sigma}{dp^3} |_{A+B \rightarrow Q+X} \sim (A.B)^{f(p_T)} E \frac{d^3\sigma}{dp^3} |_{P+P \rightarrow Q+X} \quad (3)$$

with the following subsidiary set of relations

$$f(p_T) = (1 + \alpha p_T - \beta p_T^2), \quad (4)$$

$$E \frac{d^3N}{dp^3} = \frac{1}{\sigma_{in}} E \frac{d^3\sigma}{dp^3} \quad (5)$$

where  $\sigma_{in}$  is the inelastic cross-section, A & B are mass numbers for the colliding nuclei and  $\alpha$  &  $\beta$  are the coefficients to be chosen separately for each A+B collisions (and also for A+A collisions when the projectile and the target are same).

Using all the expressions from Eq. (2) to Eq. (5), one obtains finally,

$$E \frac{d^3N}{dp^3} |_{A+B \rightarrow Q+X} = C_2 (A.B)^{(1+\alpha p_T - \beta p_T^2)} \left(1 + \frac{p_T}{p_0}\right)^{-n} \quad (6)$$

where  $C_2$  is the normalization term which includes function(s) of rapidity or rapidity density for the specific  $A + B \rightarrow Q + X$  process. By our ascription of the form  $f(p_T)$  given in Eq. (4) we introduce first what is called here De-Bhattacharyya Parametrization (DBP). The choice of this form is not altogether a sheer coincidence. In dealing with the EMC effect [*The EMC effect is just a departure of the ratio of the measured structure function of the nucleons (of deuterium and iron nuclei) through deep inelastic  $\mu\mu'$  (projectile muon and scattered muon, while the target is the nucleon - deuterium or iron) and  $ee'$  (projectile electron and scattered electron, while the target is the nucleon - deuterium or iron) scattering*[24]-[26]. *The ratios, while expected to rise with an increasing values of a scaling variable (say,  $x$ ) very slowly the results depicted first clear diminishing trends with  $x$ ; and then with further increasing values of the same the ratio began to rise modestly prominently. One of the authors here (SB) attempted to explain quite successfully this 'anomaly' with a polynomial nature of A-dependence with the same 'x'. Thus, the implication of the EMC effect is : the nucleus viewed as a collectivity of nucleons behave distinctly differently vis-a-vis the scattering processes from a single composed nucleus. This message was and is of high physical import in the realm of both particle and nuclear physics.*] in the lepton-nucleus collisions; the clue devised by Bhattacharyya[24] that resolved the complex nature of A-dependence of the ratio stimulated us to make a similar choice with both the  $p_T$  and  $y(\eta)$  variables. In recent times, this parametrization (DBP) is being applied by our group to interpret the measured data on the various aspects[22, 23] of particle-nucleus and nucleus-nucleus interactions at high energies. In the recent past Hwa et al.[27] also made use of this sort of relationship in a somewhat different context. The underlying physics implication of this parametrization has to stem mainly from the expression (6) which can be identified as a clear mechanism for the switch-over of results obtained for nucleon-nucleon ( $p+p$ ) collision to those for nucleus-nucleus interactions at high energies in a direct and straightforward manner. The polynomial exponent of the product term on  $A+B$  takes care of the totality of the nuclear effects.

The physical foundation that has been attempted to be built up is inspired by thermodynamic pictures, whereas the quantitative calculations are based on a sort of pQCD-motivated power-law

formula represented by Eq. (2). This seems to be somewhat paradoxical, because it would be hard to justify the hypothesis of local thermal equilibrium in multihadron systems produced by high energy collisions in terms of successive collision of the QCD-partons (like quarks and gluons) excited or created in the course of the overall process. Except exclusively for central heavy ion collisions, a typical parton can only undergo very few interactions before the final-state hadrons "freeze-out", i.e. escape as free particles or resonances. The fact is the hadronic system, before the freeze-out starts, expands a great deal - both longitudinally and transversally - while these very few interactions take place[28]. But the number of parton interactions is just one of the several other relevant factors for the formation of local equilibrium. Of equal importance is the parton distribution produced early in the collision process. This early distribution is supposed to be a superposition of collective flow and highly randomized internal motions in each space cell which helps the system to achieve a situation close to the equilibrium leading to the appropriate values of collective variables including concerned and/or almost concerned quantities. Further, one would note that the approach used in the present paper is an effective parametrization which is not rigorously derived. The parameter  $\alpha$  and  $\beta$  allow qualitatively for a  $p_T$  dependence of the nuclear effect as observed e.g. in  $P + A$  interactions[29, 30]. Now once more, we come back from the general discussion directly to the original issue of dealing with and completing the basic approach.

Dividing Eq. (6) for antideuteron production in  $AB$  collision by the square of that for antiproton production in the same collision one would obtain the expression for  $B_2$  with  $P_T = 2p_T$ , where  $P_T$  denotes the transverse momentum of antideuteron (antiproton).

## 4 The Phenomenological Setting for Studying Rapidity-Behaviour of $d(\bar{d})$

Following Faessler[31], Peitzmann[21], Schmidt and Schukraft[32] and finally Thomé et al[33], we [22, 23, 34] had formulated in the past a final working expression for rapidity distributions in proton-proton collisions at ISR (Intersecting Storage Rings) ranges [ $\sqrt{s} \sim 20$  GeV to 62.4 GeV in center of mass system] of energy-values by the following three-parameter parametrization, viz,

$$\frac{1}{\sigma} \frac{d\sigma}{dy} = C'_1 (1 + \exp \frac{y - y_0}{\Delta})^{-1} \quad (7)$$

where  $C'_1$  is a normalization constant and  $y_0$ ,  $\Delta$  are two parameters. The choice of the above form made by Thomé et al[33] was intended to describe conveniently the central plateau and the fall-off in the fragmentation region by means of the parameters  $y_0$  and  $\Delta$  respectively. Besides, this was based on the concept of both limiting fragmentation and the Feynman Scaling hypothesis. For all five energies in  $p + p$  collisions the value of  $\Delta$  was obtained to be  $\sim 0.55$  for pions[22, 23] and kaons[34],  $\sim 0.35$  for protons/antiprotons[34],  $\sim 0.30$  for deuterons/antideuterons. And these values of  $\Delta$  are generally assumed to remain the same in the ISR ranges of energy. Still, for very high energies, and for direct fragmentation processes which are quite feasible in very high energy heavy nucleus-nucleus collisions, such parameter values do change somewhat prominently, though in most cases with marginal high energies, we have treated them as nearly constant.

Now, the fits for the rapidity (pseudorapidity) spectra for non-pion secondaries produced in the  $p + p$  reactions at various energies are phenomenologically obtained by De and Bhattacharyya[34] through the making of suitable choices of  $C'_1$  and  $y_0$ . It is observed that for most of the secondaries the values of  $y_0$  do not remain exactly constant and show up some degree of species-dependence

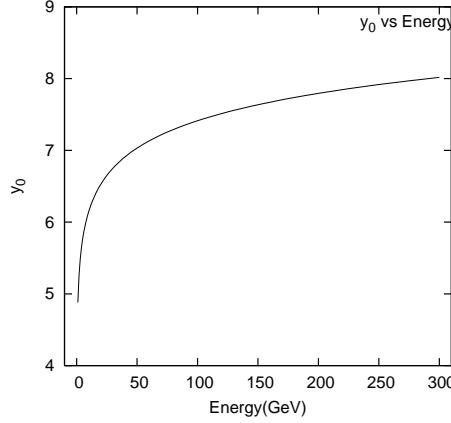


Figure 1: Variation of  $y_0$  in equation (8) with increasing energy.[Parameter values are shown in Table 1.

. However, it gradually increases with energies and the energy-dependence of  $y_0$  is empirically proposed to be expressed by the following relationship[22, 23] :

$$y_0 = k \ln \sqrt{s_{NN}} + 0.8 \quad (8)$$

The nature of energy-dependence of  $y_0$  is shown in the adjoining figure (Fig.1). Admittedly, as  $k$  is assumed to vary very slowly with c. m. energy, the parameter  $y_0$  is not exactly linearly correlated to  $\ln \sqrt{s_{NN}}$ , especially in the relatively low energy region. And this is clearly manifested in Fig.1. This variation with energy in  $k$ -values is introduced in order to accommodate and describe the symmetry in the plots on the rapidity spectra around mid-rapidity. This is just phenomenologically observed by us, though we cannot readily provide any physical justification for such perception and/or observation. And the energy-dependence of  $y_0$  is studied here just for gaining insights in their nature and for purposes of extrapolation to the various higher energies (in the centre of mass frame,  $\sqrt{s_{NN}}$ ) for several nucleon-nucleon, nucleon-nucleus and nucleus-nucleus collisions. The specific energy (in the c.m. system,  $\sqrt{s_{NN}}$ ) for every nucleon-nucleus or nucleus-nucleus collision is first worked out by converting the laboratory energy value(s) in the required c.m. frame energy value(s). Thereafter the value of  $y_0$  to be used for computations of inclusive cross-sections of nucleon-nucleon collisions at particular energies of interactions is extracted from Eq. (8) for corresponding obtained energies. This procedural step is followed for calculating the rapidity (pseudorapidity)-spectra for not only the pions produced in nucleon-nucleus and nucleus-nucleus collisions[22, 23]. However, for the studies on the rapidity-spectra of the non-pion secondaries produced in the same reactions one does always neither have the opportunity to take recourse to such a systematic step, nor could they actually resort to this rigorous procedure, due to the lack of necessary and systematic data on them.

Our next step is to explore the nature of  $f(y)$  which is envisaged to be given generally by a polynomial form noted below :

$$f(y) = \alpha' + \beta' y + \gamma' y^2, \quad (9)$$

where  $\alpha'$ ,  $\beta'$  and  $\gamma'$  are the coefficients to be chosen separately for each AB collisions (and also for AA collisions when the projectile and the target are same). Besides, some other points are to be made here. The suggested choice of form in expression (9) is not altogether fortuitous. In fact, we

got the clue from one of the previous work by one of the authors (SB)[24] here pertaining to the studies on the behavior of the EMC effect related to the lepto-nuclear collisions. In the recent past Hwa et al.[27] also made use of this sort of relation in a somewhat different context. Now let us revert to our original discussion and to the final working formula for  $\frac{dN}{dy}$  in various A+B (or A+A) collisions given by the following relation :

$$\frac{dN}{dy}|_{AB \rightarrow QX} = C'_2(AB)^{\alpha' + \beta'y + \gamma'y^2} \frac{dN}{dy}|_{PP \rightarrow QX} = C'_3(AB)^{\beta'y + \gamma'y^2} (1 + \exp \frac{y - y_0}{\Delta})^{-1}, \quad (10)$$

where  $C'_2$  is the normalization constant and  $C'_3 = C'_2(AB)^{\alpha'}$  is another constant as  $\alpha'$  is also a constant for a specific collision at a specific energy.

## 5 Results

Most of the results obtained on the basis of the models applied here are presented diagrammatically. The theoretical results on inclusive cross-sections for production of deuteron, antideuteron, proton and antiproton production in  $Pb + Pb$  collision at 158A GeV are displayed in Fig.2 and Fig.3. The solid curves in Fig.2 and Fig.3 are the presentations of the remarkably good production of the inclusive cross-section and the solid lines are the depictions of the results obtained on the basis of expression (6). The necessary parameter values related to these four figures are given in Table 2 to Table 5. The theoretical plots are made against the data-sets on normalized inclusive cross-sections versus  $p_T$  for production of deuteron, antideuteron, proton and antiproton. The DBP-based calculations show somewhat fair agreement with measured data in all these cases. These plots are being presented here in order to make a few points as particular observations : (i) The ratio-values obtained theoretically have a substantial support from the data on the basic observables. (ii) The agreement between model-based calculations and data is unlikely to be fortuitous, as it is found in such widely varied particle-species of secondaries like the deuteron, antideuteron, proton and antiproton. (iii) The testing is done here for production of  $d$  and  $\bar{d}$  in collisions with the simplest of projectile and target ( $p + p$ ) and also in collisions involving the heaviest nuclei like lead-lead. The other rapidity dependence behaviour studies for  $d$  and  $\bar{d}$  production in  $Au + Au$  and  $Si + Pb$  at different energies was made by De and Bhattacharyya[35]. This exposes modestly the wide range of applicability of the studied approach.

The four important ratio behaviours are shown in Fig.4 and Fig.5. Fig.4 shows the ratio between  $\bar{d}/d$  and  $\bar{p}/p$  and Fig.5 shows the ratio between  $\bar{p}/\bar{d}$  and  $p/d$ . The coalescence parameters for  $Pb+Pb$  collisions are plotted in Fig.6 and in Fig.7 respectively.

Some comments on the rapidity-spectra are now in order. Here we draw the rapidity-density of deuteron and antideuteron for symmetric  $Pb + Pb$  collisions at 158A GeV which have been appropriately labeled at the top right corner of Fig.8. Though the figure represents the case for production of deuteron and antideuteron, we fail to understand physically why the data depict exactly opposite nature of  $\frac{dN}{dy}$  dependence of  $d$  and  $\bar{d}$ . Besides, the solid curves in all cases-almost without any exception-demonstrate our GCM-based results. Secondly, the data on rapidity-spectra for some high-energy collisions are, at times, available for both positive and negative  $y$ -values. This would give rise to a problem in our method for studying the asymmetric collisions wherein the colliding nuclei are of non-identical nature. This is because, in our expression (10) the coefficient  $\beta'$  multiplies a term which is proportional to  $y$  and so is not symmetric under  $y \rightarrow (-y)$ . In order to overcome this difficulty we would introduce here  $\beta' = 0$  for all the graphical plots. And for symmetric

central collisions this is not an unphysical proposition or assumption. Of course, for mid-central collisions (as the case here is), we are afraid, some divergence with data-behaviour might arise. These plots are represented by Fig.8 for deuteron and antideuteron in  $Pb + Pb$  collisions. The parameter values in this particular case are presented in Table 6. The diagrams shown in Fig.9 represent the model-based results on  $\bar{d}/d$ . These plots are drawn on the basis of the figures shown in Fig.8 with the fit-parameters given in Table 6. The data-trends have been captured by our plot in a modestly right way, though it is at variance with what had been shown to be the nature of the data by the dotted straight line shown in Fig.5 by NA49 Collaboration[1].

## 6 Concluding Remarks

The approach adopted here, though new, is just purely phenomenological. Still, the method reproduces the data-trends on the  $p_T$  and  $y$ -spectra on  $d$  and  $\bar{d}$  production in the studied collision with a fair degree of success. Some predictive plot(s) in our previous work might appear to be at variance with the plots presented here. But it is to be borne in mind that the previous measurements were not centrality-based studies for which such differences between the behaviour of the past and present, data-sets are quite possible and cannot be treated as such as an ‘anomaly’. However, as data on helium-antihelium and triton-antitriton are still too sparse and they suffer from large error-bars, we have chosen not to focus on them in the present context. Our model-based values (Fig. 7) of the coalescence factor (parameters) for  $d$  and  $\bar{d}$  are somewhat less than the values depicted by pure coalescence model. The obvious implication of this is two-fold : Either the models that have been made use of here are not perfectly alright or the standard coalescence picture here has got to be modified. Still, unless the highly reliable data on deuteron, antideuteron, triton-antitriton are available, we cannot make any definitive conclusion(s) on the validity (or the lack of it), in so far as the involved physical ideas are concerned.

However, on the whole, it is quite striking to note that rapidity-density yields for  $d$  and  $\bar{d}$  are qualitatively and quantitatively in fair agreement with the data-trends measured by NA49 collaboration. And these data-behaviours are obtained just by the chosen pattern of expressions and not by any other mathematical trick. Besides, we obtain the ratio of rapidity-density of  $d$  and  $\bar{d}$  for  $Pb + Pb$  collisions at 158A ( $\sqrt{s} \approx 17.3$ ) GeV to be  $\sim 3.2 \times 10^{-3}$  and this ratio is to be checked by the future experiments. Furthermore, the  $p_T$ -dependence nature,  $y$ -dependence characteristics of  $\bar{d}/d$  ratio behaviours demonstrated by our model are, by look, almost similar. These have also to be scrutinized from the future studies.

In recent times, preliminary data on cosmic antideuteron flux[36, 37] have just arrived. Further data on cosmic  $d$  and  $\bar{d}$  from various experiments (The p-GAPS experiment)[38, 39] are expected to be available by 2017/2018. When reliable high-statistics cosmic ray data would be at hand, we would try to deal with them at appropriate time.

Despite the few successes indicated above, the main deficiencies of the present approach cannot and should not be overlooked. In our approach, there are some free parameters which must be physically identified. In otherwords, the parameters  $\alpha$ ,  $\beta$ ,  $\alpha'$ ,  $\beta'$  etc will have to be interpreted in terms of the observables of physics of collisions, like impact parameter, centrality of the collisions, number of participant-nucleons/constituents and the c. m. energy of the colliding systems etc. In order to do so what we need is more high-statistics reliable data on the measured observables.



## Acknowledgements

The authors are grateful to the two learned referees for encouraging remarks, helpful comments and some valuable suggestions.

## References

- [1] T. Anticic et al. (NA49 Collaboration), Phys. Rev. **C 85**, 044913 (2012) [nucl-ex/1111.2588 v1 10 November 2011] and the references therein.
- [2] V. I. Kolesnikov et al. (NA49 Collaboration), J. Phys. Conf. Ser. **110**, 032010 (2008) and the references therein.
- [3] C. Gang, C. Huan, W. Jiang-Ling and C. Zheng-Yu : hep-ph/1401.6872 v1 27 Jan. 2014 and the references therein.
- [4] Y. G. Ma, J. H. Chen and L. Xue, Frontiers of Physics (Springer Publication) **7(6)**, 637 (2012).
- [5] E. Shuryak, Nuclei and Atoms **23**, 501 (2010).
- [6] E. Shuryak, Prog. Part. Nucl. Phys. **62**, 48 (2009).
- [7] J. P. Blaizot, "INT @ 20 : The Future of Nuclear Physics and its Intersection", INT, Seattle (Washington), July 2010.
- [8] H. Satz, Nucl. Phys. **A 862-863**, 4 (2011).
- [9] M. J. Tannenbaum, QNP 2012, Quark and Nuclear Physics, April 16-20, 2012, Ecole Polytechnique.
- [10] J. Ellis et al., Phys. Lett. **B 233**, 223 (1989).
- [11] U. Heinz et al., J. Phys. **G 12**, 1237 (1989).
- [12] L. Canetti, M. Drewes and M. Shaposhnikov, New. Jour. Phys. **14**, 095012 (2012) and the references therein.
- [13] R. Gonzales Felife, Int. Jour. Mod. Phys. **E 20**, supp 01, 56 (2011).
- [14] F. Wikzek, Sc. America **243**, 82 (1980).
- [15] G. Basini, A. Morselli and M. Ricci, La Riv Del Nuovo Cimento 12(4), 1 (1989).
- [16] R. Hagedorn, Riv. Nuovo. Cimento **6**, 10 (1983).
- [17] B. De and S. Bhattacharyya, Eur. Phys. Jour. **A 10**, 387 (2001).
- [18] S. Bhattacharyya and B. De, Mod. Phys. Lett. **A 16**, 1395 (2001).
- [19] S. Dasgupta and A. Z. Mekjian, Phys. Rep. **72**, 131 (1981).
- [20] A. Z. Mekjian, Phys. Rev. **C 17**, 1051 (1978).

- [21] T. Peitzmann, Phys. Lett. **B 450**, 7 (1999).
- [22] B. De, S. Bhattacharyya and P. Guptaroy, Int. J. Mod. Phys. **A 17**, 4615 (2002).
- [23] B. De, S. Bhattacharyya and P. Guptaroy, Jour. Phys. **G 28**, 2963 (2002).
- [24] S. Bhattacharyya, Lett. Nuvo. Cim. **44(2)**, 119 (1985).
- [25] J. Aubert et al. (The EMC collaboration), Phys. Letts. **B 123**, 275 (1983).
- [26] A. Bodek et al., Phys. Rev. Letts. **50**, 1431 (1983).
- [27] R. C. Hwa et al., Phys. Rev. **C 64**, 054611 (2001).
- [28] L. Van-Hove, Z. Phys. **C 21**, 93 (1983).
- [29] D. Antreasyan et al., Phys. Rev. **D 19**, 764 (1979).
- [30] A. E. Brenner et al., Preprint, FERMILAB-Conf-80/47-EXP(June 1980).
- [31] M. A. Faessler, Phys. Rep. **115**, 1 (1984).
- [32] H. R. Schmidt and J. Schukraft, J. Phys. **G 19**, 1705 (1993).
- [33] W.Thomé et al., Nucl. Phys. **B 129**, 365 (1977).
- [34] B. De and S. Bhattacharyya, Int. J. Mod.Phys. **A 19**, 2313 (2004).
- [35] B. De and S. Bhattacharyya, Fizika **B 13**, 665 (2004).
- [36] I. Ibarra and S. Wild, Phys. Rev. **D 88**, 023014 (2013) [astro-ph.HE/1301.3820 v1 16 January 2013] and the references therein.
- [37] A. Vittino, N. Fornengo and L. Maccione, Proceedings of the RICAP 2013 Conference, Roma, Italy, May 22-24, 2013 [hep-ph/1308.4848 v1 22 August 2013].
- [38] S. A. I. Mognet et al. (The Prototype GAPS Experiment) : asro-ph.IM/1303.1615 v1 7 March 2013.
- [39] H. Fuke et al. (The Prototype GAPS Experiment) : astro-ph.IM/1303.0380 v3 24 June 2013 [Accepted for publication in Advances in Space Research]

Table 1: Variation of  $y_0$  with Energy.

$Energy(AGeV)$	$\sqrt{s_{NN}}(GeV)$	$Constant(k)$	$y_0$
20	6.3	2.76	5.894
30	7.6	2.54	6.006
40	8.7	2.40	6.085
80	12.3	2.16	6.276
158	17.3	1.97	6.463

Table 2: Different parameter values for deuteron production in  $Pb + Pb$  collisions at 158A GeV

$Centrality$	$C_3$	$\alpha$	$\beta$	$p_0$	$n$	$\frac{\chi^2}{ndf}$
0 – 12.5%	$0.363 \pm 0.003$	$0.563 \pm 0.001$	$0.099 \pm 0.001$	$4.366 \pm 0.008$	$26.664 \pm 0.043$	1.675/10
12.5% – 23.5%	$0.272 \pm 0.003$	$0.500 \pm 0.001$	$0.097 \pm 0.001$	$4.996 \pm 0.016$	$26.236 \pm 0.075$	2.877/10
0 – 23.5%	$0.319 \pm 0.002$	$0.563 \pm 0.001$	$0.102 \pm 0.001$	$4.366 \pm 0.009$	$26.331 \pm 0.049$	2.032/10

Table 3: Different parameter values for antideuteron production in  $Pb + Pb$  collisions at 158A GeV

$Centrality$	$C_3$	$\alpha$	$\beta$	$p_0$	$n$	$\frac{\chi^2}{ndf}$
0 – 12.5%	$0.0008 \pm 6.098 \times 10^{-6}$	$0.215 \pm 0.001$	$0.136 \pm 0.001$	$13.300 \pm 0.104$	$21.307 \pm 0.162$	1.824/03
12.5% – 23.5%	$0.0009 \pm 1.716 \times 10^{-5}$	$0.113 \pm 0.002$	$0.050 \pm 0.002$	$11.999 \pm 0.151$	$22.942 \pm 0.278$	1.068/03
0 – 23.5%	$0.0009 \pm 4.613 \times 10^{-6}$	$0.157 \pm 0.001$	$0.055 \pm 0.001$	$11.415 \pm 0.043$	$24.359 \pm 0.089$	0.525/03

Table 4: Different parameter values for proton production in  $Pb + Pb$  collisions at 158A GeV

$Centrality$	$C_3$	$\alpha$	$\beta$	$p_0$	$n$	$\frac{\chi^2}{ndf}$
0 – 12.5%	$51.669 \pm 0.233$	$0.338 \pm 0.001$	$0.139 \pm 0.001$	$4.985 \pm 0.010$	$17.932 \pm 0.031$	12.035/11
12.5% – 23.5%	$42.023 \pm 0.201$	$0.321 \pm 0.001$	$0.134 \pm 0.001$	$4.000 \pm 0.007$	$15.017 \pm 0.024$	13.810/10
0 – 23.5%	$51.937 \pm 0.260$	$0.309 \pm 0.001$	$0.127 \pm 0.001$	$5.000 \pm 0.009$	$18.001 \pm 0.028$	11.064/10

Table 5: Different parameter values for antiproton production in  $Pb + Pb$  collisions at 158A GeV

$Centrality$	$C_3$	$\alpha$	$\beta$	$p_0$	$n$	$\frac{\chi^2}{ndf}$
0 – 12.5%	$5.092 \pm 0.031$	$0.400 \pm 0.001$	$0.123 \pm 0.001$	$5.000 \pm 0.012$	$24.750 \pm 0.054$	3.869/14
12.5% – 23.5%	$3.733 \pm 0.028$	$0.320 \pm 0.001$	$0.120 \pm 0.001$	$4.923 \pm 0.017$	$20.004 \pm 0.066$	8.483/14
0 – 23.5%	$4.460 \pm 0.024$	$0.350 \pm 0.001$	$0.122 \pm 0.001$	$4.785 \pm 0.011$	$21.000 \pm 0.046$	3.495/14

Table 6: Values of different parameters for production of deuteron and antideuteron in the 23.5% most central  $Pb + Pb$  collisions at 158A GeV (for  $\beta'=0$ ) for both +ve and -ve rapidities.

$Production$	$C'_3$	$\gamma'$	$\frac{\chi^2}{ndf}$
$d$	$0.242 \pm 2.70 \times 10^{-4}$	$0.034 \pm 0.0001$	0.160/03
$\bar{d}$	$0.001 \pm 1.00 \times 10^{-6}$	$-0.050 \pm 0.0001$	0.016/03

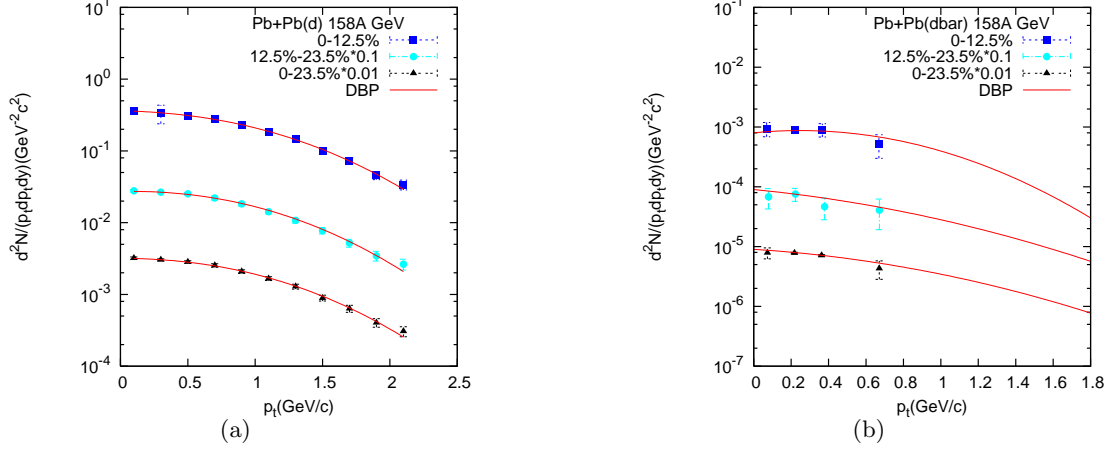


Figure 2: The transverse momentum spectra of deuterons (a) antideuteron (b) in centrality selected  $Pb+Pb$  collisions at 158A GeV. Only statistical errors are shown. The experimental data are taken from [1] and the parameter values are taken from Table 2 & Table 3. The model-based results of the present work are shown by the solid curves.

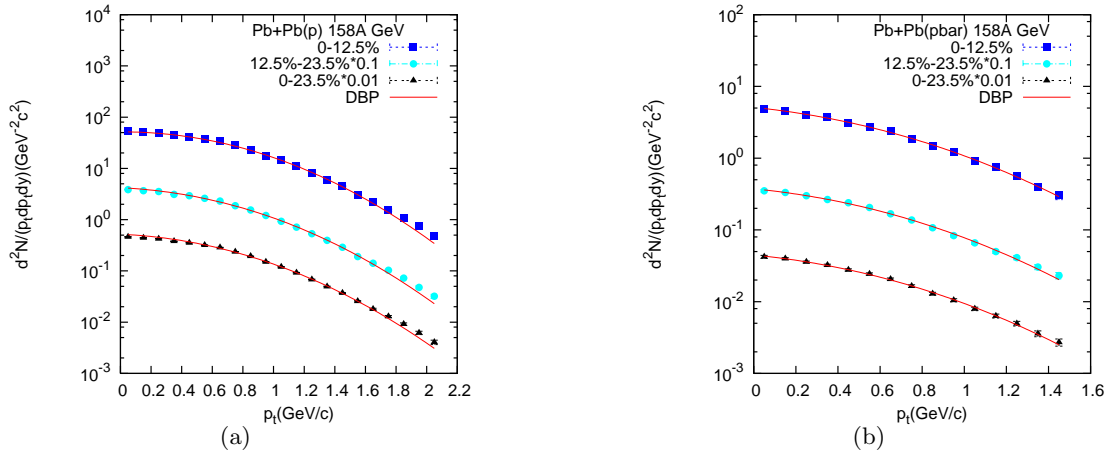


Figure 3: The transverse momentum spectra of protons (a) antiprotons (b) in centrality selected  $Pb+Pb$  collisions at 158A GeV. Only statistical errors are shown. The experimental data are taken from [1] and the parameter values are taken from Table 4 & Table 5. The solid curves provide the present model-based results.

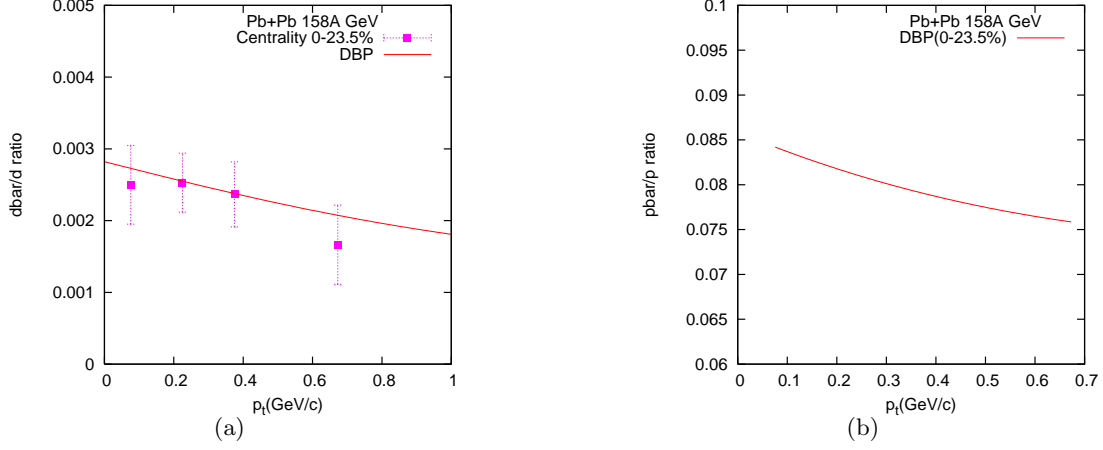


Figure 4: (a)  $\bar{d}/d$ -ratio as a function of  $p_T$  in 0-23.5% central Pb+Pb collisions at 158A GeV and (b) Predictive nature of  $\bar{p}/p$ -ratio with respect to the transverse momentum ( $p_T$ ) in 0-23.5% central  $Pb + Pb$  Collisions at 158A GeV on the basis of present model. The experimental data are taken from [1].

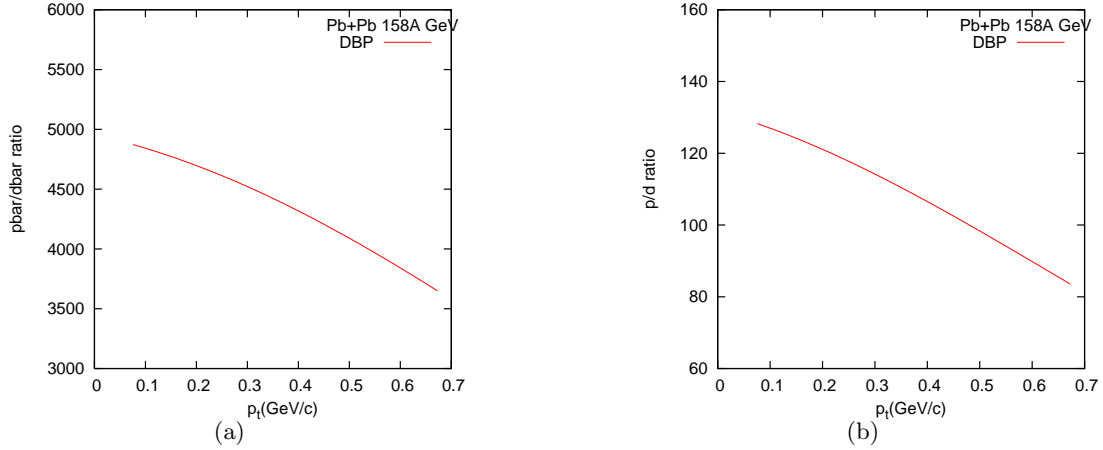


Figure 5: Predictive nature of  $\bar{p}/\bar{d}$ -ratio and  $p/d$ -ratio with respect to the transverse momentum ( $p_T$ ) in 0-23.5% central  $Pb + Pb$  Collisions at 158A GeV on the basis of present model.

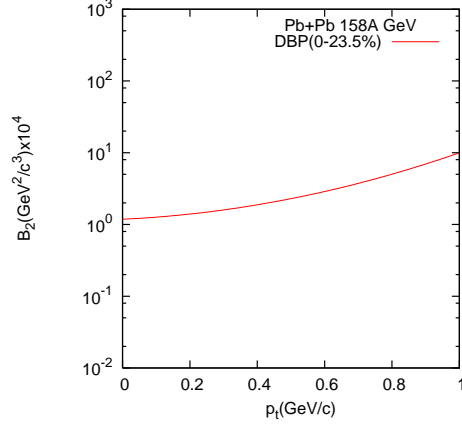


Figure 6: Plot of Coalescence parameter  $B_2$  as a function of antideuteron transverse momentum  $p_T$  in the case of  $Pb + Pb$  collision. The solid curve depicts the DBP-based results.

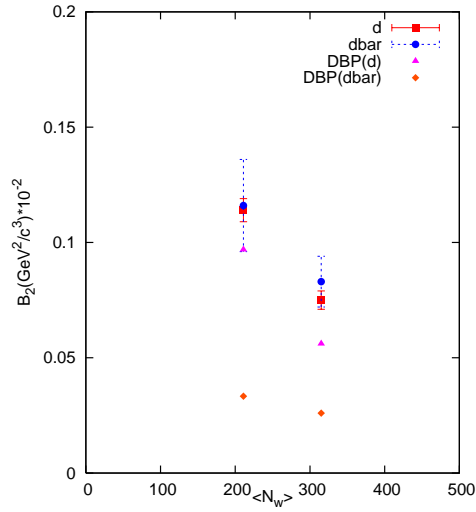


Figure 7: Plot of Coalescence parameter  $B_2$  for  $d$  and  $\bar{d}$  calculated from DBP-model in centrality selected  $Pb + Pb$  collision at 158A GeV.

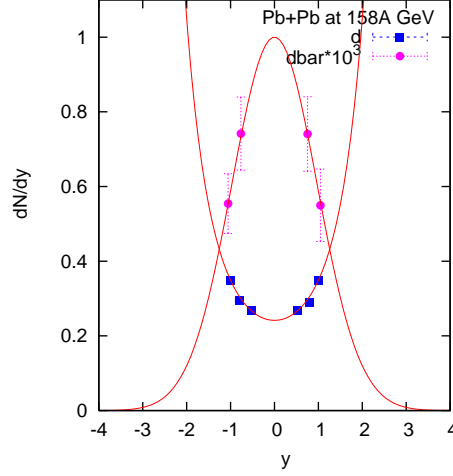


Figure 8: Rapidity-density distributions for  $\bar{d}$  (circles) and  $d$  (squares) produced in the 23.5 % most central  $Pb+Pb$  collisions at 158A GeV. The symbols are the experimental data and the data points are taken from [1] and the parameter values are taken from Table 6. The solid curve provide the GCM-based results.

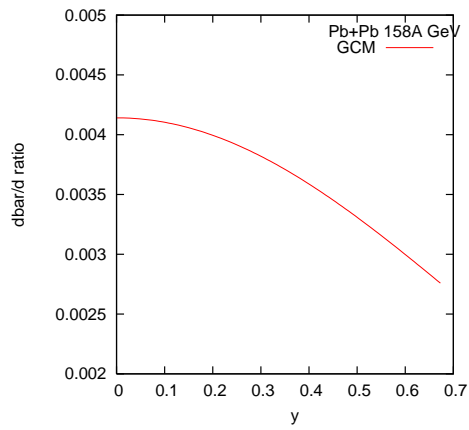


Figure 9: Predictive nature of  $\bar{d}/d$ -ratio with respect to the rapidity ( $y$ ) in 23.5% central  $Pb + Pb$  Collisions at 158A GeV on the basis of GCM-based results.